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Decarbonising power generation in China—Is the answer blowing in the wind?

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ABSTRACT

This paper examines the current situation of wind industry development, evaluates the potentials of GHG mitigation and identifies the key determinants of scaling up wind power deployment in China. China has doubled its wind capacity every year for the past 4 years, the total installed capacity reached 12 Gigawatts (GW) and surpassed the 10-GW target 2 years ahead of schedule in the national plan for renewable energy development [38,71,87],and would reach 100–120 GW by 2020 according to the government's new energy plan. It may become the biggest wind power generation and wind turbines manufacturing country of the world in the next years if the abundant wind resources and enormous domestic market can be harnessed with appropriate policies and efficient technology. The recent positive move in vigorous development of wind power in China implies that the total installed capacity will far exceed the targets of the government's 2007 renewable energy plan. However, the prosperous Chinese wind market has also revealed some worrisome signals and weakness [28,58], such as low capacity factor and frequent outage of wind farms, inadequate grid infrastructure, long distance transmission, low quality of turbines, adverse price bidding, nepotism in wind farm developer selection process and regulatory uncertainty and policy inconsistency which all conspire to hinder effective power generation in the massively new installed wind capacities. A coherent policy framework is required for creating enabling environment for accelerating wind energy penetration and state-of-art technology deployment in the country. It is argued that institutional, financial and technical capacity will need to be cemented to exploit the huge potentials of wind resources to meet the rapidly growing demand for electricity in China in the coming decades with minimised environmental implications.

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1. Introduction

Developing renewable electricity generation has become an imperative to decarbonise China's energy supply on a par with significant improvement in energy efficiency across all the economic sectors for the next decades. Past experiences in industrialised OECD countries show strong coupling of economic growth with electricity production and consumption [106]. Empirical studies confirm the GDP/electricity correlation for the cases of China and other developing Asian countries [76,99,108]. Currently nearly 80% of electricity in China is generated from coal, two 500 megawatt (MW) coal-fired power plants per week are constructed in the country, and one 500 MW coal-fired power plant produces approximately 3 million tonnes/year of carbon dioxide [63]. Demand for electricity will invariably increase in China over the next decades due to urbanisation and growing standard of living. Power supply would more than tripling by 2030. Coal-fired power plants in China would account for nearly one-quarter of increase in global energy related CO_2 emissions during the period 2005–2030 under the business as usual scenario [2]. A typical coal-fired power plant is expected to operate at least 35–40 years, posing a daunting challenge for climate change mitigation.

Wind is considered as the most promising renewable energy technology for power generation. It is expected to play an increasingly important role in addressing the challenge of energy supply security and mitigating climate change in the world. Wind is regarded as an alternative resource with the most realistic chance to displace large amounts of fossil fuel combustion and curb greenhouse gases (GHG) emissions [37,38,88]. IEA projects that in 2050 wind power could supply up to 12% of global demand for electricity—with concentrated effort and technological innovation [3]. Germany has even set an ambitious target to raise wind electricity's share in power generation to 30% by 2020 and 50% by 2050 [36]. Denmark has established similar target (50% of energy production will come from wind power by 2050 [15]). Optimistic projection indicates that wind may contribute to 10–12% of global electricity consumption by 2020 with a 1500-Mt CO_2 emissions cut per year, and it could supply as much as 21–30% of global electricity demand by 2050 in the advanced scenario [38].

Vigorous development of wind energy can generate a broad array of positive externalities, such as contribution to security of energy supply, reduction in GHG emissions otherwise emitted from fossil fuel-fired power plants, pollution control and natural resources savings, increasing job creation opportunities (wind turbine manufacturing and installation have so far a market of €36.5 billion and created more than 400 000 jobs in the world), and enhanced economic competitiveness in the low-carbon and environmentally friendly technologies R&D, upgrade of industry supply chain, reduced cost of renewable electric power generation. Most importantly, diffusion of wind energy technology contributes to improvement in people's welfare , in particular in rural and remote areas where centralised electrification is not available. It is noteworthy that still one-quarter of world population(around 1.6 billion) and over 70 million people living in remote rural areas in China do not have access to conventional electricity service [48,120], while the model of centralised thermal power plant coupled with long distance transmission and distribution networks are unsuitable in these regions due to technical difficulty and economic inefficiency.

Endowed with abundant wind resources in the north and southeast coast of the country, China has experienced considerable growth in the wind energy development over the past years and has become one of the world's leading countries in wind energy both in terms of installed generating capacity and wind industry development. Statistics show that the cumulative capacity installed of wind power totalled 12.2 GW by the end of 2008, making China the fourth biggest wind power country after the USA, Germany and Spain [40,87], 2 years ahead of the revised national renewable energy plan. China is expected to overtake Germany and Spain to become second country in terms of generating capacity by 2010 with 30 GW installed capacity [23,24], which will make China achieve the national renewable goals a decade ahead of political agenda in the national renewable energy development plan [72], formulated by National Development and Reform Commission (NDRC), the national economic and energy policy maker and energy market regulator.

The latest projections of BTM consulting indicate that the installed capacity in China could reach 35.5 GW by 2012 [14], 8 years ahead of the schedule of the national plan. The Global Wind Energy Council (GWEC) estimates that China could scale up its wind power capacity to 100 GW by 2020 in order to make significant contribution to energy security and climate change mitigation. From political standpoint, the newly established Energy Bureau of NDRC stated that the development of renewable energy will play a crucial role in the power supply of China. Wind energy development in China is now on a fast growth track and globally, the Chinese energy policymakers believe that wind power will become the primary alternative energy in the future [18].

The Chinese policy makers are very keen on mass deployment of wind energy throughout the nation. The central government has made great effort to encourage the wind energy scale-up since 1990s through a number of policy support, regulations and laws, which trigged the wave of all-round investment in the wind energy across the country since 2005. Some large-scale projects are being planned and expected to be realized in several provinces. The NDRC has granted high priority to development of wind power generation in the energy policy agenda for the coming years. According to NDRC [72], thirty 100 MW-scale units of wind farms

will be installed by the end of 2010 and three 1 GW-scale wind farms will be constructed in Jiangsu, Hebei and Inner Mongolia [98]. More recently, China's national energy administration selected six provinces for Mega wind-power base project in Xinjiang, Inner Mongolia, Gansu, Hebei and Jiangsu, with the objective of developing 10 GW or more wind farms year by 2020 on each of selected sites. The mega-bases will ensure 100–120 GW generating capacity producing more than 200 teraWatt hours (TWh) per year, a crucial component to achieve the 3% of non-hydrorenewable electricity target by 2020 [21,39,73,80,84,111].

However, despite the spectacular growth in installed wind capacity over the past years, large wind power potentials in China still remain untapped and a significant part of installed generating capacity is left idle or under performing. More specifically, many installed capacities are actually sitting idle in the far north and northwest inland provinces with sparse population, the domestically made turbines are often underperforming or have difficulty in connecting to power grid due to technical, financial and institutional barriers. Building on a comprehensive review of existing literature, this paper provides investigation into the potentials of scaling up of wind power and the technical, economic and institutional implications for the wind energy industry development in China. The overriding aim is to address the question how China can harness its abundant wind resources by tailoring sound policy support and appropriate instruments to decarbonise its power supply cost-effectively, the successful deployment of large-scale wind power generation will make substantial contribution to climate change mitigation for avoiding the long-term carbon lock-in. Like other developing countries, China is required to adopt low-carbon development pathways by increasing investment in new technologies which provide emissions reduction while securing energy supply [31].In this regard wind can play a crucial role in decarbonising China's leapfrogging power sector cost-effectively, provided an integrated approach is adopted to safeguard the success of harnessing wind resources in China in the next decades.

2. Wind energy and climate change mitigation

2.1. Imperative of reducing carbon emissions in the power sector

In China, electricity generation and demand have been growing steadily in parallel with the leapfrogging economy over the last decades, particularly there has been exponential rise since 2002, as depicted in Fig. 1. The annual power generation increased more than 5-fold during the period 1990–2007, growing from 620 TWh to 3277 TWh per annum, and total installed generating capacity reached 623 GW in 2007, compared to 127 GW in 1990. China's power sector is heavily reliant on coal, more than 60% of new generating capacity are coal-fired, posing a formidable challenge for environmental protection and climate change mitigation since

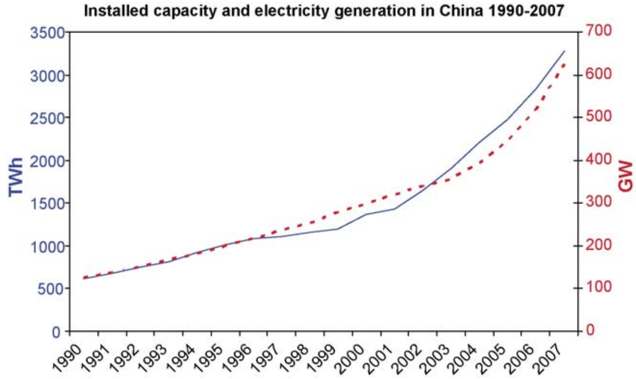

Fig. 1. Evolution in China's power sector 1990–2007 [13,33,67].

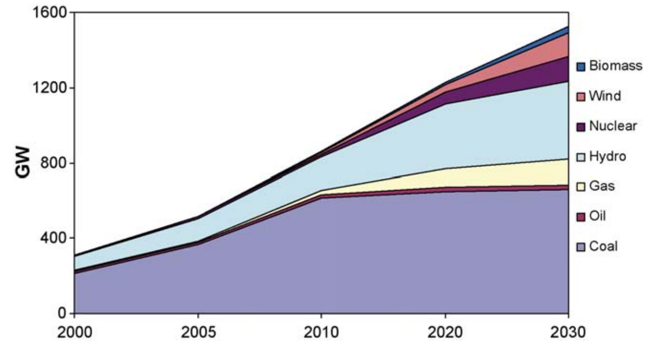

Fig. 2. Projected power generation capacity in China under BAU (source [44]).

coal is a major resource of combustion-related GHG and pollutants emissions in the country. In 2005, China accounted for 19% of global energy related carbon emissions of which nearly 50% were emitted from coal-fired power plants [2].

China's power sector is expected to continue growing steadily to fuel its socioeconomic growth in the next decades, around 1000–1300 GW new generating capacity would be added between 2005 and 2030 [2,4,44], exceeding the total installed capacity of European Union in 2030! More specifically, about two-thirds of the coal-fired power plants built in China by 2020 will still be operational in 2050. These plants alone represent a commitment of roughly 2–3 billion tonnes of annual CO_2 emissions until 2050 [103]. However, despite fast development of renewable energy, coal will continue to dominate the energy supply, in particular in power generation in China under the BAU scenario (see Fig. 2). High dependency on coal could lock China in the high-emissive trajectory for several decades since the prospects for clean coal and carbon free technologies such as CCS still remain highly uncertain. Decarbonising power supply by developing alternatives has thus become an imperative in China by encouraging low-carbon and carbon free electricity generation technologies.

The Chinese government has revised periodically the target of the long-term energy strategic plan in order to take the fast growing renewable energy development into account. In 2007, NDRC aimed to raise the share of renewable energies to 15% of total energy supply by 2020, non-hydropower was planned to represent 1% and 3% of total electricity generation in the areas covered by large power grid by 2010 and 2020 ,and generating capacity of wind was planned to reach 30 GW by 2020 [73]. According to the projection of [44], wind power is assumed to reach 45 GW in 2020. More recently, the government is likely to raise the target of wind power capacity to 100–120 GW in the year 2020 by taking the recent fast wind power development into account [80,101], though these figures show that wind energy will still represent a small fraction of the total power generating capacity (around 3–4%),and almost negligible compared with the huge potentials for wind resources in China, in particular in the western provinces and coastlines.

2.2. Great potential of wind energy

Globally, the available wind energy resources are estimated at 20 TW, or about 10 times that hydropower resources that can be used. Even if 1% of the wind energy potential were exploited globally, 8–9% of the current total electricity generation in the world could be met [3]. Recent study also shows that 20% of world wind power potential at 80 m above ground could supply more than 7 times current global electricity consumption [43]. World wind energy has developed rapidly in the past decade. The generating capacity of wind energy is growing at 20–30% per year, and the total installed capacity surpassed 120 GW in 2008 [38].Wind is contributing increasingly to the world power generation, approximately

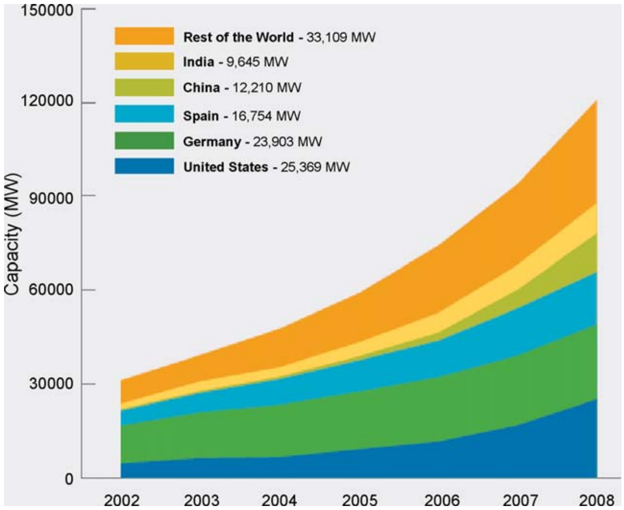

Fig. 3. Global total installed wind power capacity (source: extracted from [7]).

152 TWh of wind electricity were generated in 2006. Annual investment topped US$ 50 billion in 2007 [3]. Fig. 3 delineates the past trend of development in the major wind-power development countries. US surpassed Germany to become the world wind power leader in terms of installed capacity in 2008.

China is endowed with abundant wind resources. According to the estimates of the Chinese Meteorological Administration(CMA) on the basis of 900 meteorological observation centres in China, on the relatively low height of 10 m above ground, the theoretically exploitable wind resource represents a potential power generation capacity of 4.3 TW and the practical onshore potential is around 253–297 GW, the offshore wind potential is much higher and may be three times that of onshore potentials [53,68]. In 2007, the national research showed that the onshore technically feasible wind resource totalled around 600–1000 GW and offshore potential is estimated at around 300 GW [53,96], thus the higher estimate of onshore and offshore potentials is equal to the projected increase in total power generating capacity in China during 2005–2030 period in [2,44]. The Chinese wind industry estimates that as much as 170 GW wind power capacity could be installed by 2020 [52] with strong policy support in the wind sector. In a recent paper published in the PNAS, Lu et al. calculate the global potential for wind electricity, their simulation shows that large-scale development of wind power in China could offer 18-fold increase in electricity supply, of which nearly 90% could be derived on onshore wind farms[57].

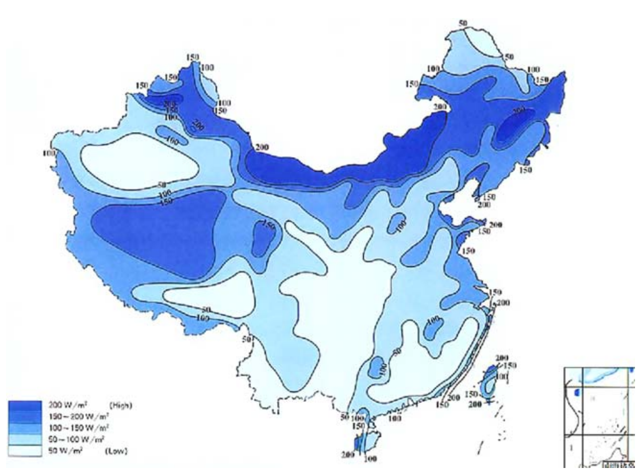

Fig. 4. Distribution of effective wind power density in China (W/m^2) (source [19]).

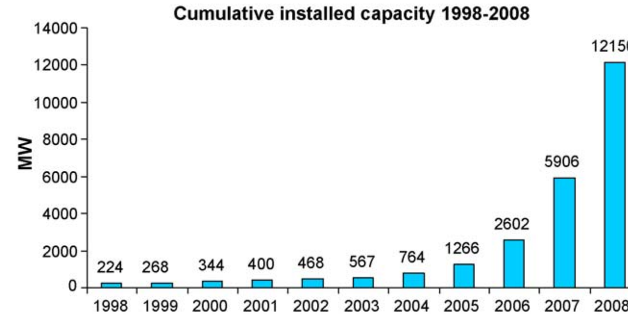

Fig. 5. Development of cumulative installed wind power capacity in China 1998–2008 (source [53,86]).

Fig. 4 provides an overview of the distribution of wind energy resources in China in terms of effective energy density. The most abundant wind resources are located in southeastern coastal area: Fujian, Jiangsu, Shanghai and Shandong, and inland northern provinces: Manchuria, Hebei, Inner Mongolia, Gansu, Ningxia and Xinjiang.

2.3. Unprecedented rate of rapid development of wind energy in China

China's wind energy has experienced extremely rapid development over the past years, China used to be an insignificant market for wind power before 2004. Yet just 4 years later, it has become one of global wind energy development leaders. The average growth of wind power capacity rise was 40% during the period of the 10th five-year plan. Total cumulative installed capacity increased more than 50-fold, growing from 224 to 12150 MW during the last decade (cf. Fig. 5). The yearly new capacity addition grew from 58 MW in 2000 to 6240 MW in 2008, or more than 100-fold increase. The increase has been particular strong from 2005, since then the annual increase rate is more than 100%, total installed capacity of wind farms doubled for the fourth year in a row over the period 2005–2008. In 2006 alone, total generated capacity increased 105% [40,53]. It is projected that China will reach its wind production target of 30 GW in 2010, a decade ahead of schedule set in NDRC [73]. China is planning to build six major mega wind-power bases (10 GW scale wind farm) in Xinjiang (Hami region), Gansu(Jiuquan), Inner Mongolia, Liaoling, Hebei, Jiangsu [21,71,100]. Around 12 GW would be installed in Gansu province alone, and 60 GW in the other four huge mega-bases by 2015 [100].

Despite its rapid increase, wind still represents only a tiny fraction in the electricity generation in China. The annual rise in wind power generation capacity (6000 MW) represents only 7% of total power generation capacity addition in 2008 (90 000 MW). According to the Chinese Wind Energy Association (CWEA), grid-connected electricity generated in the wind power plants is estimated at 12 TWh in 2008, accounting for only 0.35% of total generated electricity which amounted to 3400 TWh [66].

3. Co-benefits and prospect

3.1. Energy security and environmental and social benefits

It is widely recognised that wind energy is one of promising ways to enhance energy security and minimise negative environmental externalities by cutting fossil fuel combustion-related carbon emissions economically with available technologies. As mentioned in [55], increasing renewable portfolio will diversify the supply and reduce the risk of energy supply disruption and price volatility on the fossil energy markets, since the increasing dependence on imported oil and gas raises the concerns about

security of energy supply, the highly volatile oil price and geopolitical constraints of natural gas supply render the national economy more vulnerable and less sustainable. Developing reliable domestic renewable resources such as wind is one of effective countermeasures to minimise the risks of disruption. From energy conversion system's perspective, wind can make a significant reliability contribution given a reasonably high wind speed. Wind energy independence also has a significant positive impact on the reliability contribution of multiple wind energy conversion systems [125]. Developing wind power can also help improve local air quality and reduce the environmental hazards to improve public health[1]. Wind power generation can also reduce significantly natural resources consumption such as water consumption. Note that the conventional fossil fuel-fired and nuclear power plants are very water intensive, water consumption is more than 500 gallons per MWh electricity produced [118].

From life-cycle analysis perspective, within 3–6 months of operation, a wind turbine has offset all emissions caused by its construction, to run virtually carbon free for the remaining 20-year life. Globally, about 260 TWh wind power electricity is generated and avoided 158 Mt CO_2 emissions in 2008, and optimistic projection of wind energy development in the world will allow cutting 1.5 billion tonnes CO_2 in 2020 [40]. The total installed wind generating capacity in China reached 12.2 GW in 2008, taking a relatively conservative average 2000 h full capacity in all the wind farms in operation, the total wind electricity generated is estimated at 24.4 TWh per year, counteracting 23 Mt CO_2 emissions from coal-fired thermal power plants per year[2], which is equal to the total emissions in Croatia in 2007 [5]. The recently planned wind power target (120 GW installed by 2020) would allow offsetting more than 226 Mt CO_2 from the coal-fired power plant in 2020. Furthermore, a power plant will be operating at least 20–25 years once constructed, thus the lifetime emissions savings potential of the existing wind capacity in China in 2008 may amount to more than 800 Mt CO_2 from 2008 to 2030[3]. In addition, wind energy can also reduce the air pollutants resulting from power generation, it is reported that for each 1000 kWh generated from wind farm in China, 2.1 kg of soot[4], 4.76 kg of SO_2 and 31.5 kg of solid waste can be avoided compared with the conventional coal-fired power plants. Additionally, 2520 kg of fresh water and 290 kg coal could be saved [58,89].

3.2. Socioeconomic benefits: creation of employment opportunities

Development of local wind turbines manufacturing can generate several positive economic spillovers [49,79]:

a economic development opportunities by creating new firms in the supply chain, job creation as well as increased local tax base
b potential possibility of exporting domestically made turbines to international market
c cost savings in wind farms project development and thus lower cost of wind electricity. In a typical wind farm construction project, the turbine accounts for nearly 70–80% of investment cost, high dependency upon imported turbines and generation appliances have been the major hurdle to scaling up wind power generation in many developing countries where local technical know-how and production capacity have not been built up. This is even much truer in the countries where labour costs are significantly lower such as India and China, since some component of wind turbines system such as tower is labour intensive and low technology-intensive [49]. Put aside the labour cost, turbine and equipment shipment costs can also be lowered significantly, as well as cutting road and maritime transport related GHG emissions.

Further, development of wind farms can also allow the local industry to ramp up the supply chain gradually. The past experiences of wind industry evolution in China show that the domestic turbine manufacturing firms have built up the technical capacity and consolidated the localised market share. More than 60% of wind turbines installed in China are now produced within the country [86]. Moreover, most of wind farms are located in remote and underdeveloped area, where poor transport infrastructure constitutes a major hurdle to socioeconomic development. Development of wind farms can attract investment by bringing finance[5] in infrastructure improvement to facilitate goods and people mobility and to help poverty alleviation [58].

Globally, UNEP estimates that investment in low-GHG energy will reach $1.9 trillion by 2020 [94]. From global perspective, to address the world financial crisis, the US government launched a comprehensive green energy stimulus for economic recovery plan may reach a value of $400–$500 billion. Green investments will total about $15 billion per year, more than 2.5 million green jobs would be created over the next 2 years. Obama's green stimulus plan covers a variety of measures in energy efficiency and renewable energy and smart grid development. Wind power development contribute effectively to the economic growth and job creation, it is reported that that each wind turbine needs more than 8 000 machine parts. From global perspective, for one billion US$ investment in wind energy in the United States, about 3300 jobs may be created [27][6]. In China, green capital investment grew from $170 million in 2005 to more than $720 million in 2008. Currently, the global wind industry employs more than 400 000 people around the world and may reach 2 million by 2020 [38]. 325 000 jobs would be created in the EU for wind resources development by 2020 [38]. More importantly, wind industry development can create new job opportunities. Currently, the renewables sector employs nearly a million people in China, most in the wind industry [91], the planned wind mega-bases will offer large potentials for job creation in China in the next 20 years, which has extremely important political implication for China since the mass joblessness will endanger the socioeconomic stability.

4. Situation of wind industry in China

4.1. Development of wind energy in China

Wind energy development[7] in China started in the late 1970s and early 1980s in the form of demonstration with foreign government grants and loans [53]. The initial projects were located in remote area to supply shepherds in Mongolia autonomous region, most were off-grid stand-alone small wind turbines at that period. The first grid-connected wind farm was built in inner Mongolia in 1989 and imported American made 100-kW turbine

[1] Environmental and public health impacts of coal burning by the ten biggest power companies in China are estimated to be RMB 87 billion (US$ 12.7 billion) in 2008 [111].

[2] Emissions from coal mining, extraction and transport are excluded in the calculation.

[3] This does not take into account the decommissioning of existing wind turbines since most of wind farms have been constructed in the last years.

[4] Black carbon emission is the second biggest contributor to global warming, see [70]for more technical detail.

[5] Wind farm developers are required to finance the infrastructure development in the concession project.

[6] Jobs related to wind turbine manufacturing, installation, distribution networks development are included in the estimate.

[7] This refers to power generation, albeit the Chinese began harnessing wind energy thousands years ago.

[58]. Wind had not been perceived as alternative energy resource to coal until the 1990s. According to the recent literature [53,79,83], China's wind energy research and development (R&D) and market development can be divided into three major stages:

(i) The first stage covers the period 1980–1995. The wind turbines units R&D in China started in early 1980s focusing on grid-connected small units (less than 200 kW). Most of the experimental turbines could not meet the market demand with large capacity. During this period, Denmark, France, Spain, Germany and other countries supplied government loans and grants to Chinese government for small-scale wind power demonstration projects, by adopting foreign advanced technology, a number of wind power generation units rated at 120 kW, 200 kW, 250 kW and 300 kW had been developed successively. On the other hand, the domestic manufacturing quality was unreliable and the performance of units did not allow for commercial exploitation of the large-scale wind farms. Therefore the existing wind farms at that period only used imported wind turbines or key components. In 1992, China imported 250 kW fixed-pitch turbines generators from Germany and several dozens of such units were installed in Manchuria, Inner Mongolia and Hainan provinces. In the meanwhile, the Danish leading wind turbine manufacturer, Vestas also exported turbines to China. However, the high-cost of imported turbines had significantly hindered the fast deployment of wind farm in wind-rich regions. The wind electricity price was subsidised and fixed by the national government at 0.3 yuan/kWh during this period, comparable with the coal-fired electricity [52].

(ii) Since 1990s, the Chinese government has introduced a series of policy mechanisms and measures to promote the development of indigenous wind turbine technology manufacturing industries, including domestic wind turbines R&D speed-up and establishing joint-venture firms with large foreign manufacturers such as Danish Vestas and Spanish Gamesa. These policies are designed for encouraging local wind industry to accelerate technological know-how acquisition, enhancing economy and creating local wind-related job opportunities. During the 1990s, China experienced stagnation and slow-down of wind farm construction, China did not meet the initial target of 200 MW installations by 1995 and 1000 MW by 2000[8]. From 1995 to 2003, the Chinese government unveiled a range of policies and incentives to encourage the scale-up of domestic wind energy industry development since utilisation of imported units is only feasible for small-scale projects construction and development of the initial stage. The early stage of wind farm development was concentrated on small scale demonstration projects with foreign government loans and technical assistance, and these projects also benefited from tax free and reduction policies offered by local government. In addition, imported units also require foreign expertise and technical intervention in the maintenance, repair and equipments technology.

Thus high dependency on imports of units for large-scale wind farms development posed a challenge of costs. For example, the imported units were 900–1000 US $/kWe of capacity on the wind market, in comparison, the most deployed coal-fired thermal power plants in China was less than 700 US$/kWe [95]. Consequently, the Ministry of Science and Technology (MOST), launched a batch of S&T advancement projects such as "National 863 hi-tech scientific research plan", to promote the development of wind power technology. In 1996, the former Ministry of Electric Power launched "Ride the Wind Program" to stimulate wind farm development and domestic wind industry. The former State Economic and Trade Commission (SETC) and the Planning Commission initiated the "Double-plus project"[9] in 1997 and "National bond project" in parallel with "Ride the wind" project to promote domestic wind industry during the 9th and 10th five-year plan periods. Over 900 million RMB (108 million US$) soft loans were provided to install large wind turbines with a total capacity of 81.6 MW in Inner Mongolia, Xinjiang, Zhejiang and Hebei [56]. During this period, the stall-controlled fixed pitch wind turbines with capacity rated at 600 kW and 750 kW were developed, the domestically made (both Chinese and joint-venture companies) turbines became dominating the market share.

(iii) Since 2003, NDRC launched *wind farm concession* projects to promote large-scale commercialisation of wind farms with a guaranteed grid-connection tariff, determined by tendering process [124]. To be eligible for concession project, the wind farm should have a capacity higher than 100 MW and individual turbine unit installed must be no less than 600 kW [52]. More specifically, for each concession project, in which at least 50% turbines should be made domestically (revised to 70% from the second stage of concession projects) to support and encourage the domestic wind turbine industry as well as creating domestic wind market. For example, in 2004, Xinjiang Gold Wind Technology developed 600 kW and 750 kW turbines with production capacity of more than 100 units per year. To keep in pace with large-scale development of domestic wind turbine industry, China has gradually developed auxiliary industries such as blade, wheel hub, gearbox, generator, yaw system and electric control systems specializing in the production of plant parts, though some key components are still heavily dependent upon imports [53,79].

It must be pointed out that the national strategy with regard to wind energy development is to improve the quality of domestically made turbines by adopting mature foreign technologies to produce major parts and components domestically and compete with international leaders [49,53]. In January 2006, the *Renewable Energy Law* (REL) came into force which specifies the policy measures to promote renewable electricity. The REL legitimizes a feed-in tariff framework for renewable power generation technologies and establishes grid integration requirements and standard procedures. It establishes cost-sharing mechanisms such that the incremental cost will be shared among utility consumers. It also creates new financing mechanisms and support renewable energy development in rural areas [62,69]. More recently, the NDRC adopted the Medium- and Long-Term Development Plan for Renewable Energy in China in 2007 [73], the plan states that "*higher grid connection prices should be offered to new and renewable energy providers, and renewable energy portfolio standards should be established in a timely manner, with full support*". Most renewable electricity has been developed according to this guideline hitherto.

4.2. Current situation of wind turbine industry and market share

Until very recently, most of turbines and equipments in the wind farms projects in China were imported from wind-leading countries (i.e. Germany, Spain, Denmark and India). Since 1990s, these multinational companies have established joint-venture with local producers or independently to exploit the Chinese

[8] The actually installed capacity was only 345 MW by the end of 2000 [56].

[9] Accelerate investment and improve efficiency in large-scale wind farms localisation and wind turbines industry development.

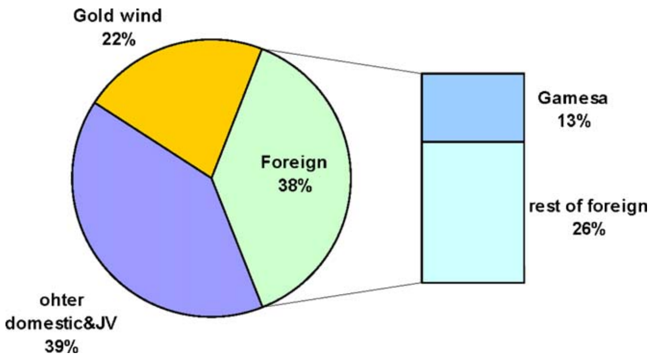

Fig. 6. Statistics of market share of Chinese domestically made an imported wind turbines in 2008 (source [86]).

market potentials. Foreign companies of turbine manufacturing dominated the Chinese wind energy market. In 2006, foreign and joint ventures combined accounted for nearly 60% of market share [53]. However, this situation was reversed in 2008 when the domestically-based wind turbine manufacturers (Chinese and joint ventures) surpassed the foreign companies to dominate the nation's whole wind energy market with a share of 61% [86],of which the country's leader *Gold Wind* gained more than one-fifth of the total market and 35% of domestic production capacity. The Spanish turbine manufacturer– Gamesa is the leading foreign turbine supplier in the Chinese market with more than 12% of total market share and one-third of the foreign supply capacity. Fig. 6 illustrates the share of domestic and international turbine manufacturers in the Chinese wind market in 2008.

Table 1 summarises the production capacity and market share of the major domestic and foreign turbine manufacturers in China. The three biggest domestic manufacturers, Sinovel, Gold Wind and DEC together accounted for more than half of increase in installed capacity in 2008, while Vestas, Gamesa and GE are the major foreign actors in Chinese wind energy market. Domestic manufacturers account for three-quarters of the increase in the wind market in 2008.

Table 1
Breakdown of market share of foreign and domestic wind turbine manufacturers.

	Installed capacity in 2008 (kW)	% of capacity installed in 2008
Foreign manufacturers		
Vestas	599700	9.60%
Gamesa	508300	8.14%
GE	145500	2.33%
Nordex	144000	2.31%
Sulzon	128500	2.06%
Domestic and JV manufacturers		
Sinovel	1402500	22.45%
Gold wind	1131750	18.12%
DEC	1053000	16.86%
Windey	178750	2.86%
Mingyang	174000	2.79%
CASC-Acciona	150000	2.40%
XEMC	120000	1.92%
New Unite	73500	1.18%
Beizhong	60000	0.96%
others	130180	2.08%

Source: [86].

4.3. Regulatory framework and pricing mechanism

There are basically two types of wind farm projects in China, namely government contract and concession projects, respectively [58]. The government contract projects are approved by the NDRC or provincial DRC depending on the installed capacity[10]. Under this scheme, wind farms are operated by power companies which constructed the wind farms while the purchase of wind power is controlled by national government. Price of wind electricity is decided by the power purchasing agreement (PPA), endorsed by NDRC and wind power companies. The price is calculated by taking generation costs and reasonable profits rate into account. Once the wind farms come in operation, wind power companies' income is almost guaranteed since grid companies have obligation to purchase the generated electricity [58].

In 2003, China introduced a system of wind farm concession in which the on-grid price of wind power must be determined by tendering process and then approved by the government [53]. In addition, the price will also be negotiated with the grid company in every different instance. A two-stage pricing policy of wind power is implemented in the concession project. First, for the electricity generated during the first cumulative 30000 h, the price submitted by the accepted project developer in the bidding process is implemented. Second, after the first period, the average grid price (based on competition with other fuel including coal) will be applied. The concession period generally lasts 25 years [52]. For a typical wind farm with an average capacity factor of 25%, the feed-in tariff will last about 15 years. Based on the REL, the *Regulation on pricing and expenses sharing in renewable power purchase* and the *Provisional regulation for establishing a feed-in tariff for renewable energy power and distribution* have been adopted and implemented since 2007, in which the methodology of determining subsidy of renewable power is specified. The regulation stipulates that renewable power price range should be approved by the price administration of the State Council and monitored by the State Electric Power Supervision Committee [72,73].Price ranged between 55 US$/MWh and 86 US$/MWh in different wind farm concession projects in 2007 [53]. This is relatively comparable to the international wind energy market, globally, the generation cost of on-shore wind power generation ranges between 75 US$/MWh and 97 US$/MWh depending on quality of wind resources of the production site [3]. As for European wind market, costs of onshore wind farms are between 45€/MWh and 87€/MWh [105].

However, many wind power projects tend to favour the lowest-price offer during the bidding process (the weight of price represent more than 40% in the project bidders selection criteria), it may occur that some developers misestimate the wind resources and underestimate the operation costs of wind farms, or the price submitted to regulatory authority in the bidding document can not even allow the operator to cover the costs let alone the margins and benefits, which is extremely discouraging for the new entrants, in particular the international players in wind energy development. Furthermore, the current model of concession project bidding is opaque and lack of transparency since the local authorities prefer to choose the domestic developers [28].

4.4. Breaking the barriers to entry and local capacity building

Recent development of wind industry has been moving to large turbines (1–5 MW scale turbine) with variable speed, and the wind turbine manufacturing industry has been concentrating in a small number of large, financially strong international firms [59]. Large turbine becomes more and more technically sophisticated in pitch regulation and electric control system. Many leading wind turbine manufacturers have spent several decades in technology innovation, new products R&D since the first oil crisis in 1970s. Previous studies show that technology transfer may or may not include

[10] Projects with less than 50 MW installed capacity can be approved by provincial DRC (local subsidiary of NDRC), otherwise the NDRC will be responsible for decision making [58].

technological know-how transfer, furthermore, the transfer of "hardware" (component, equipment of turbines) by purchase of licence of production without transfer of "software" (training of workforce and knowledge dissemination) will not trigger the supply chain establishment in importing countries since wind turbine manufacturing is a complex system, a typical turbine consists of more than 900 components. Moreover, large turbines manufacturing requires necessarily robust turbine performance design (to extract maximum energy resources) and components production, and poses the challenge of advanced aerodynamics and hydraulic modelling and wind infrastructure, in particular for the offshore wind farms as well as power grid integration [59]. Integrated supply chain includes turbine design, manufacturing, installation and operation and maintenance, yet many local wind industries in China have just started very recently and have not acquired sufficient competence.

On the other hand, several international wind industry leaders are aggressively predominating global wind markets backed by their technical know-how, good reputation (e.g. Siemens, GE, etc.) and integrated supply chain. Danish Vestas has already established turbine manufacturing factories in China and supplies full generation system and components to the Chinese wind market. Currently, 90% of Vestas turbine components are produced locally. For instance, the V60-850 kW turbine is tailored to the inclement weather in northern China and to optimise electricity generation efficiency with the low- and mid-speed wind resources.

Moreover, the issues related to the intellectual property rights (IPRs) may also constitute a potential barrier to new technology deployment in recipient countries due to competition concerns. How to share the scientific and technology discoveries, R&D in the wind industry is of critical importance. It is reported that many multinational firms still withhold the key technical know-how of turbine component and put constraints on local employees to information disclosure [49]. According to [98], nearly 70 domestic firms in China produce full wind turbines, however, most of them do not possess their own IPRs and few of them have established R&D capability. Some "opportunist" firms just replicate foreign technology and investment blindly in the wind power markets without systemic technical feasibility and market prospects study.

National support and policy mechanisms play a crucial role in promoting domestic wind industry. For example, In Germany, wind energy development has been strongly backed by the federal government in public policies. By 2007, 19,460 wind turbines with a total capacity of 22,247 MW were installed in Germany. 40.4 TWh of wind electricity was generated, accounting for nearly 7.5% of Germany's electricity consumption in 2008 [38]. It is projected that wind power will account for 12.5% of electricity generation by 2010 and 20–25% by 2020 [39]. More importantly, German manufacturers of wind turbines and components represent 37% of the global market share with over six billion euros in exports in 2007. The sector currently employs more than 100,000 people [38]. Similarly, Denmark is the one of the leading countries in wind power development. Wind is expected to account for 40–50% of electricity consumption in Denmark by 2020 [104,113]. The Danish manufacturer Vestas, the largest turbine supplier in the world sold over 99% of its products in overseas markets in 2004 [49].

In developing countries, India is an illustrative example of fast wind energy development, both in terms of domestic capacity installation and international market consolidation. In 2008, cumulative installed capacity reached 9.6 GW, more than 40-fold relative to 2000. Indian government has made strategic development plan of wind turbines manufacturing industry. India has consolidated domestic wind turbine manufacturing base, the national leader Suzlon is the world's fifth largest turbine manufacturer and has also well established in the international wind market beyond India, operating in 20 countries around the world [38]. The Indian experience can be a good reference to the Chinese wind policy makers in light of seizing the great potentials of both domestic and international markets of wind power to develop the global leaders of wind turbine manufacturer. Useful lessons can also be learnt from the solar industry in China, in particular the solar thermal whose development has experienced dramatic growth, some major solar industry player in China have become global leaders in solar photovoltaic (PV) and solar thermal manufacturing[11].

5. Difficulties beneath the water surface

5.1. Imbalance between wind resources potentials location and power demand centre

According to [53], wind resources in China can perfectly complement hydroresources since wind is abundant in spring , autumn and winter while hydro is plenty is summer, however, the geographic distribution of wind resources do not match well the power demand due to the long distance between supply and demand centres, since most of east provinces with large demand for electric power have few wind resources while most of abundant high-quality wind resources (north east and north west provinces in particular) are located in the remote parts of western and northern China with sparse population and far away from electricity demand centres [38,48]. China would need to build large-scale, long-distance and high-voltage transmission grid to transmit electricity to densely-populated regions where demand for electricity is much higher, posing enormous engineering and financing challenges. The existing capacity of long-distance transmission grid networks are inadequate, and the regional grid interconnection lags behind the increasing demand as well. The imbalance between wind resources rich regions and demand centres constitute the stumbling block of scaling up the wind power development in China.

5.2. Intermittent power supply and quality of domestic wind turbines

Wind is a highly variable energy source and behaves far differently as compared with conventional energy sources. The wind turbines differ fundamentally from the conventional generators in that their power output is not settable/controllable by the operator and primarily depends on the wind speed [10,30], wind fluctuation can have significant impact on the turbine performance and power output. Despite the immense energy potentials in China, wind is characterized by diffuse, intermittent and unpractical for transport disadvantages compared to fossil fuels. Inherent technical difficulty needs to be addressed albeit the unfavourable characteristics can be dealt with engineering solutions with proven technologies [17].

In addition to the inherent shortcoming of supply intermittence, the under-performance and inefficiency of local turbine products and difficulty in grid connection constitute another major hurdle to private investment in wind farms project development and mass deployment of this promising low-carbon power generation technology. Although the installed capacity of wind energy in China increased exponentially over the past years, many of the wind farms have encountered technical obstacles. Many installed wind turbines are running under productive level quite frequently, i.e. underperforming due to unfit geographic site

[11] China is already the top market for solar thermal water heating systems which are currently more cost-effective than PV systems [85].

selection with prevailing low-speed wind. Some installed capacities are left idle or under-exploitation due to inefficient or unsuitable site design[12]. The average capacity factor[13] is above 30% in developed countries, whereas it is only 23% in China [28].

In fact, wind turbine performance is site-specific, choosing the most ''adaptive'' turbines in a particular wind park is of extreme importance since different turbines are designed to operate nicely under particular wind condition, if a turbine is not chosen appropriately, the wind turbine performance will deteriorate and the overall energy efficiency of wind farms will plummet as a result [71,114]. The under-performance of domestically made turbines becomes a serious problem in many wind farms, the brakes are usually once a month in the world while in China once every 4 days. For instance, out of the 5.7 GW installed in 2007,only 4 supplied electricity to the power grid [28]. Most turbine breakdowns are produced by gearbox of which the bearings are determinant factors for ensuring the good quality of operation.

The study of Blanco [105] shows that full-capacity operation hours is the most important factor influencing the per kWh wind electricity generation cost. Low capacity factor in these wind farms make the cost of wind kWh significantly higher than conventional coal-fired power plants in China, subsequently, the grid companies are more reluctant to purchase wind electricity albeit it is greener.

It is noted that wind farms using foreign models have a 5% higher capacity factor than that using domestic models on average [28]. Similarly, based on a comparative study of a panel data of a number of representative manufacturers active in the Chinese market, Wang et al. [95] find that the performance (in terms of theoretical power generation) of imported units are on average 20% higher than domestically made turbines under the same wind condition in two representative wind farm concession projects in Jilin and Jiangsu provinces. In addition, the low quality of customer service warranty is another weakness of domestic manufacturers compared with the well-known international players [87].

5.3. Power integration and grid performance-related technical barriers

The unparalleled rapid development of wind power in China poses a challenge to grid infrastructure since most large wind farms are located in far north and northwest China with sparse population. The state-owned grid company's grid expansion plan follows closely the national electric power development plan which is issued by the central government, however, the national plan can hardly keep up with the explosive new capacity addition across the country, including the renewable power plants. For example, the objective of wind energy in the medium- and long-term plan for renewable energy [73] was to reach 5 GW in 2010 which is surpassed in 2007 and 30 GW in 2020 which is likely to be beat by 2013 [14].

Integration of wind facilities into power system grids have several impacts on power system related issues, including transmission congestion, optimum power flow, system stability, power quality, system economics and load dispatch [34]. Further, wind power has a random, intermittent, mostly anti-adjustment features, large-scale wind turbine grid incorporation would result in grid peak shaving, increased complexity of operation mode arrangement, and safety and stable operation of power grids could be affected to a certain degree as well. Most importantly, integration of large scale wind farms to the public grid affect the power quality and may have severe impacts on the power system operation due to the effects of voltage fluctuation (instability), flickers, voltage asymmetry and harmonics [104]. The penetration of large wind power may also cause the reduced reserve power capacity due to the necessary redispatch of conventional power plants [60]. How to ensure stable, reliable and economic operation of the power system under the massive integration of wind power is a critical challenge for power system operators [104].

As hydropower resources, large wind power potential are located in remote areas with relatively weak grid infrastructure, and the local electricity markets are still underdeveloped, lack of regulatory support for developing the means of electricity transmission infrastructure consisting of transmission lines, transformation substations and other power grid facilities which are often overloaded, incorporation of large wind farm would have significant impact on grid security in terms of stable operation and supply reliability. High-voltage and long-distance transmission lines need to be developed and involve large investment. It can be estimated that grid capacity weakness will constitute the major bottleneck of scaled development of large wind farms in the west of China in the next years.

5.4. Institutional issues: taxation, pricing and standard

The Chinese government has already initiated tax incentives in favour of domestic industry and wind electricity generation. In 2002, the Ministry of Finance (MOF) reduced the value-added tax for wind electricity generators from 17% to 8.5% [68]. However, the recent tax reform on VAT transformation (entered into force in January 1st 2009) would have reverse impact on wind industry indirectly. According to this reform, VAT in wind industry will be transferred from production-based to consumption-based tax, i.e. the expenses in purchasing equipment will be allowed to be deducted from the wholesale benefits. From national tax policy perspective, indeed, taxation compensation incentives on wind turbine components will allow reducing tax burden for wind turbine manufacturing firms, however, the local government will see a significant shrink in tax base in the industry localised in their jurisdiction accordingly, thus a disincentive for the local government to attract wind industry localisation [51].

On the other hand, the custom tariff rate on imported wind turbines and components is one of the main reasons that make wind farm capital costs significantly higher than coal-fired power plants, as a large number of wind power projects import the turbines and equipment from abroad [93], turbines and equipment costs account for more than 70% of wind farm investment [56,95,114,115]. Therefore the instrument of preferential tariff must be used with care for the sake of protection of domestic wind industry. Tariff rate of import of entire turbines and components ought to be differentiated smartly since some key technology-intensive components of turbines, such as the main bearings and electrical control system are still highly dependent upon import [53,58]. Actually, import custom tariff for turbine and components was lowered to 8% (reduced from 12%) and 3%, respectively, in 2004, however, the VAT of imported turbine components is still 17%, thus the extra cost in a wind farm using imported equipment is above 20% [95].

The MOF issued a new regulation of tax refund for importing large wind turbines and components for 1.2 MW and above units from January 2008. Meanwhile, the tariff free advantage is cancelled for turbine unit less than 2.5 MW from May 2008 [64]. The tax rebate will go directly to the central government and then be channelled back into the wind industry through special programme. More recently, the MOF introduced another policy which recompenses the first 50 wind turbines rated at 1 MW and above with approximately 90 US$/kW, provided that the

[12] Each type of turbines is fit for a particular wind regime. Wind shear, turbulence and inclined airflow are among the most important parameters that influence the uncertainty of the power curve measurements in wind farms [107].

[13] Which is defined as the ratio of the actual output of a power plant over a period of time and its output if it had operated at full rated capacity the entire time.

turbines are produced by domestic or joint venture companies (Chinese share should be above 51%). The two policies are not exactly compatible and inconsistent since the first encourages imported products while the second tends to protect local manufacturers, albeit these policy incentives will certainly foster the R&D and technology innovation as well as improving competitiveness of domestic manufacturing to some degree [38].

Although some provinces have implemented the income tax reduction policy to encourage the wind energy, there is no national policy on income tax incentives, all the wind farms are subject to the universal rate 33% (since 2008 the income tax for power generation in wind farms is reduced to 15%) , irrespective of geographical location or type of technology employed, albeit a 50% tax rebate may be granted in the case of concession projects to refinance the project follow-up.

Another hurdle to the improvement of wind farm energy performance is rooted in the current wind price bidding system in the concession project. The price bidding model tends to favour the companies or developers which agree to supply electricity at the cheapest price to grid operator or utilities consumers at the expense of wind turbines quality, sometime even at unprofitable base [71]. It is noted that some bidders intentionally underestimate operating costs to get a lower grid-connection price compared to other bidders [58].In the long run, this nepotism is likely to result in adverse selection process that will drive away foreign developers with mature technology and good experiences in wind farm operation and management, there would eventually be a risk of creating the market for 'lemon' [6].

The lack of standards is also another barrier to good installation and operation of wind farms. It is common that consistent policy framework is wanting, many wind generators have persistent difficulty in selling electricity generated to power grid. However, appropriate policy framework with strong signal of public authority regarding the renewable energy policies are the prerequisite of scaled deployment of wind energy in China. Transition from niche market to scaled commercialisation will necessarily require strong intervention of public policies in the initial development stage.

Since 2005, the Chinese government imposes a mandate on concession wind farm projects that must rely 70% of turbine parts on domestic manufacturers in order to boost local wind industry. In fact, the protectionism will undermine the development and localisation of advanced renewable energy technologies since wind turbine manufacturing and industrialisation in China started very recently. Introduction of foreign products is an essential part of endogenous financial development and technological learning during the initial stage of domestic industrial takeoff. Xia and Song [98] project the wind industry development prospect in China with logistic modelling method and find that wind industry is still in the Spring period of the growth cycle which is composed of four "seasons", the fastest growth rate will be attained around 2015 (summer). Thus during the start-up period, policy support mechanisms such as preferential subsidy and tax and tariff reduction are required to enhance the learning-by-doing and foster the sectoral capacity building to achieve the objective of industrialisation of domestic turbine manufacturing, installation, maintenance and management.

5.5. Lack of comprehensive development strategy

As noted by Qin [79], despite the enforcement of renewable energy law and implementation of the medium- and long-term targets of wind power development, no comprehensive measures and approaches have been adopted by both central and local government, and the research in wind energy technology still lags behind the expected targets. A blueprint for comprehensive Chinese wind energy industry growth strategy (capacity building in both human resources and technical know-how) needs to be specified by policymakers and sectoral experts, the whole value chain of wind energy industry should be taken into account in the strategic plan. More specifically, the analyses of technical difficulties mentioned earlier demonstrate that there is still large room for quality improvement with regard to many key technical components in wind farms, technological and research breakthrough in the domestically made wind turbines need to be addressed to optimise the wind farm operational performance and increase the average capacity load. Innovation is still a weakness in the wind industry in China like many other industrial sectors[14]. Although domestic players have been more active in wind farms development and operation, most of the turbines installed and key components are imported from abroad(Liu et al. [56]; Qin [79]; Lewis and Wiser [49]; Li et al. [53]; China Newenergy [20]; Xia and Song [98]). Many domestic manufacturers do not have their own IPRs and technological innovation and are still simply importing or replicating the foreign technologies without necessarily acquisition of the capacity of implementing systematic approach of research, development, deployment and commercialisation of wind power, integrated sectoral approach are required to be enhanced by creating synergy between the industries through the whole supply chain, the small and medium companies still account for the bulk of wind industry, national industry leader like international players such as Gamesa, Vestas and Sulzon is expected to be built up. Thus coherence and consistency are key condition of the successful policies in wind energy scale-up. IPR will play a critical role in the market competition in the following years while the huge domestic market is expected to be opened further to international players and multinational companies specialized in wind energy both in turbine manufacturing and wind farms operation management, this provides both challenges and opportunities for the Chinese wind industry to upgrade itself to win the competition. The next couple of years will be a critical period for the Chinese wind energy industry in terms of sectoral growth and technological upgrading and capacity scaling up.

6. Great leap forward of China's wind power

6.1. Policies and measures for scaling up

6.1.1. Regulatory framework and policy support for technological breakthrough

Wind power has been developing steadily over the last decades. In the comprehensive review on the global wind technology status, Ackermann and Söder [60] find that grid-connected wind capacity has doubled worldwide approximately every 3 years in the 20th century. Scaled wind development in China has occurred since recent years. As mentioned earlier, the Chinese government has introduced a series of policy measures to encourage renewable energy development both from the perspective of energy supply security and industrial ramping up. NDRC [74] emphasised the importance of large-scale development of wind energy and promoting technology improvement to foster domestic manufacturing capacity and to reduce costs and enhance the market competitiveness of wind power. Diversified energy supply by using clean and carbon free alternative technologies such as wind will allow the country to reduce the risk associated with single fossil fuel supply portfolio and to develop new impetus for sustainable economic growth as well as reducing the power-related GHG and pollutants emissions. The government has established the policy support framework building on a series of

[14] More than 80% patents in many core high economic sectors in China are owned by developed countries companies [31].

regulation and specific policies such as renewable energy premium, mandatory purchase of renewable electricity, tax and fiscal advantages, incremental cost sharing and special fund for renewable energy development and scale-up. However, it is still commonplace that many policy support mechanisms are coincident with the national 5-year plan, to the detriment of policy continuity and likely to raise the uncertainty about the return on investment, the consistency and relevance of policy objectives are of crucial importance to ensure the effectiveness of policy implementation.

Performance of wind energy conversion depends upon subsystems like wind turbine (aerodynamic), gears (mechanical), generator (electrical); whereas the availability of wind resources are governed by the climatic conditions of the region concerned for which wind survey is extremely important to exploit wind energy [8]. Scaling up wind energy in power generation requires mobilising the whole supply chain of wind industry and relevant research institutions. Improving the performance of turbines and wind farms and reducing the cost of power generation in terms of $/kWh are key elements to successful diffusion and deployment of wind energy, the most influencing factors of cost-effectiveness in wind energy investment are the capital cost, O&M cost and full-operation hours and easiness of access to capital finance and stability of political framework [105,114]. Therefore developing new materials and technology to lower the installation costs and increase the capacity factor are determining factors to make wind power competitive in the electricity market. Bansal et al. [8] indicate that design and successful operation of wind energy conversion systems is a very complex task and requires interdisciplinary skills, e.g., civil engineering, mechanical, electrical and electronics, geography, aerodynamics, aeroelastics, materials, environmental sciences, etc. Appropriate policies are needed to encourage cooperation between academia and industrials to accelerate research & development in wind technology-related sectors with comprehensive approach. Furthermore, the policy support and incentives provided in the previous scale-up programmes such as *Ride the wind* and *double-plus* should be systematized and integrated into the long-term national energy policy framework.

6.1.2. Mega-bases of wind power generation

In 2008, the Chinese government initiated an ambitious plan to construct six mega wind-power bases rated at the order of magnitude of 100 GW in the wind resources rich regions by 2020: Inner Mongolia, Gansu, Xianjiang, Hebei and Jiangsu [87], of which 20 GW in Xinjiang, 50 GW in Inner Mongolia, 10 GW in Hebei, 10 GW in Jiangsu (7 GW offshore)[15]. The first mega base project which consists of eight large-scale wind farms has started in Jiuquan (Gansu) in 2008 with a total installed capacity of 12 GW by 2015, investment will be totalled at 120 billion RMB (17.6 billion US$), which will be the largest wind farm in the world (People's Daily [77]).

To transmit electricity generated in the west to the load centres in east China poses techno-economic challenge since this will involve long-distance (several thousands km) high-voltage transmission lines, huge capital will need to be mobilised to develop the grid infrastructure. The State Grid Corporation, China's biggest power supplier is committed to doubling its investment in grid infrastructure modernisation in 2009 and 2010 as well as regional interconnection. Local governments in advanced wind energy regions are also very keen on grid upgrading issues, the province of Gansu plans to invest 20 billion RMB (2.9 billion US$) in grid to support the megabase project, and a 30-billon RMB (4.4 billion US$) investment is planned to be invested in grid operations by the provincial government of Inner Mongolia by 2010 [28]. Private initiatives and other innovative financing tools are necessary to bridge financing gap in power grid capacity expansion.

"Three Gorges wind farm" project in the Inner Mongolia

Inner Mongolia encompasses the largest wind resources in China, it has more than 100 000 MW wind resources potentials of which 3 000 MW has been exploited hitherto. The local government plans to build up the "Three Gorges wind farm" in China by 2010, when the total installed wind power capacity will reach 5 GW.

Inner Mongolia is one of the earliest provinces in wind power development, initially the stand-alone wind turbines were developed and primarily used for the herdsmen in the 1970s and 1980s [58]. Construction of the first large wind farm—Huitengxile started In 1996 and reached an installed capacity of 68.5 MW in 1999 (there are six phases in total), annual electricity generation is expected at 157 GWh. In recent years, backed by the national and local policy to strengthen the development and utilisation of renewable energy, wind power development in Inner Mongolia accelerated significantly, the installed capacity amounted to 600 MW at the end of 2006, then more than doubled to reach to 1650 MW one year later, and exceeded 3000 MW in May 2009,ranking the first in China.

Inner Mongolia has also become the country's major manufacturing base for wind power generation equipment. As of the end of 2008, Inner Mongolia had 16 wind power equipment manufacturing firms, of which five have been completed and put in operation, the total wind related investment reached more than 2.7 billion RMB; the planned manufacturing capacity was 4560 MW, of which 1430 MW has been commissioned.

Source: China Newenergy online [22].

In the meantime, the large-scale development of wind energy offers great opportunity and market potentials for wind turbines manufacturing in China. According to a recent announcement by the Chinese Climate Change Info-Net, Jinan, the capital city of Shandong province, will build the nation's largest wind turbines and equipment manufacturing base from March 2009. With an investment of 3 billion RMB (430 million US$), this manufacturing hub will be able to supply more than 500 units of wind turbines per year to wind resource rich provinces after completion by 2015 [25].

6.1.3. Exploiting economies of scale through learning by doing

The mega-bases are likely to make wind more attractive for grid-connected power generation by creating economies of scale that will allow lowering the risk of uncertainty by bringing down the cost of electricity generation. The mass deployment and concentration of large wind farms will drive the technology innovation and catalyse the formation of integrated supply chain of wind industry. Past experiences in the global market show that turbine costs have decreased by a factor of 4 since the 1980s. In 2007, onshore turbine costs ranged from US$ 1.2 m to 1.8 m per MW and 1.8–2.2 m$ per MW for offshore wind farms [105],the cost of a typical 2-MW onshore wind turbine installed in Europe is around 1225 €/kW, of which approximately 75% is related to upfront costs such as the cost of the turbine manufacturing and electrical equipment installation, grid-connection and so forth. The per kWh wind-generated electricity is around 7¢€ for the average wind speed regime in European wind farms [115]. However, wind farm construction costs could rise in the short run due to insufficient supply of turbines and components, as well as commodity and raw materials prices escalation.

Intense efforts have been made by the economists to model the experience curve in the renewable energy development. The experience curve describes how unit costs decline with cumulative production [90]. The curves demonstrate that investment in the deployment of emerging technologies could drive prices down so as to provide new competitive energy system for CO_2 stabilisation [1]. For example, the global photovoltaic (PV) market has experienced dramatic growth over the last 30 years driven by learning effect. Nemet [75]and Neij [90] argue that economies of scale play essential role in learning curves for renewable energy, the average capital cost of PV was reduced by 20% every doubling of installed capacity in the world over the last 30 years. As for wind energy technology, one of the market leaders, Danish turbines'

[15] It was recently announced that another mega base has been planned in Inner Mongolia region [21,80].

progress ratio of the experience curve was 92% over the period 1982–1996, i.e. for each doubling of cumulative installed capacity of wind turbines, the price per kilowatt was reduced by 8% [90]. Similarly, cost of produced wind electricity has decreased steadily over the past two decades, the cost of per kWh wind electricity is reduced by more than 50% compared to 20 years ago [105]. It is also found that every doubling the generation capacity of wind power in the world has resulted in reducing per kWh cost by 9–17%,based on comparison of literature of international experiences. The long term cost reduction is expected to continue in the wind industry. The European Commission's energy models project that the capital cost of onshore and offshore is expected to decrease 40% and 46% by 2020 [112]. Neij [90] estimates that the average cost of wind-generated electricity will almost be reduced by half by the year 2020 by assuming the market would grow at 15–20% annually. More specifically, the process of technology learning requires long-term, stable policy support. Therefore considerable investments – known as *learning investments*– may be required over the next few decades [1]. Policy instruments *push* of governments are determining factors to accelerate the learning and technology diffusion and promote market *pull* to drive the cost down further.

In fact, Chinese wind industry has already built up considerable capacity in wind technology R&D. For example, China has developed the world's first permanent magnetic levitation wind power generator – namely MagLev generator, and is being regarded as a key breakthrough in the evolution of global wind power technology. The MagLev generator is expected to boost wind energy generating capacity by as much as 20% over traditional wind turbines. The MagLev is able to utilize winds with starting speeds as low as 1.5 m/s, and cut-in speeds of 3 m/s [50].

However, under current electricity market competition environment in China, the wind farms using imported turbines cannot compete with coal-fired power plants due to high capital cost. Previous studies show that mass domestic production in China can drive down the cost of turbines by as much as 40% [47], and the combination of oversized wind farms with storage systems can compete with coal-fired power plant in terms of life-cycle cost of kWh produced, provided that the capacity factor of wind farms concerned can reach relatively higher level than that in most existing wind farms in China. Moreover, wind energy has lower risk in terms of variable costs(in particular the fuel cost) compared with coal-fired power plants, since coal price is expected to increase continually in the next years due to higher mining cost and capacity bottleneck of transport[16] as well as more stringent environmental regulations. Moreover, the global energy production will see increasing carbon emission constraints with the long-term targets of GHGs mitigation(translated into an explicit carbon price). Although China is not subject to quantitative emission cap yet, it is likely that the post-Kyoto climate regime will put certain degree of emission constraints in the Chinese power sector, a carbon tax could be levied by the Chinese government based on coal consumption in the near future [78]. Note that the central government has recently announced an objective of reducing GDP's carbon intensity by 40-45% by 2020 [121]. On the other hand, carbon capture and storage (CCS) options will increase dramatically the production costs in coal-fired power plants[17], let alone the uncertainty about the feasibility, geological storage availability and legal issues of this technology option.

[16] Coal transport accounted for nearly 40% of rail freight capacity in China in 1990s and reached nearly 50% by 2008 [48,65].

[17] The cost of a kWh electricity produced in CCS plants may increase by 22–65%, even up to 80% depending on composition of the flue gas, the volume of effluent to be processed and capture technologies [82].

6.2. Improvement in wind power capacity factor with hybrid and storage systems

The major geographic and technical constraints such as wind intermittence and asymmetry between supply and demand for power can be coped with an integrated system combining oversized wind farms, large-scale electrical storage and long-distance transmission lines to deliver "baseload wind power" to distant electricity demand centres in China [47]. The key element of transforming intermittent wind energy into baseload power supply is related to increasing the capacity factor to reduce the cost of delivered electricity by high-voltage transmission lines [16,48]. However, the large demand centres in China are far away from wind resources rich regions in the north and northwest, wind electricity can be transmitted in long-distance transmission lines but at expensive costs.

Another solution is related to using hybrid wind power system backed by large-scale storage facility to transport wind power cost-effectively such as pumped hydroelectric storage, batteries, regenerative fuel-cells, flyheels, superconducting magnets and compressed air energy storage (CAES) [17,48]. Intermittent wind power can then be transformed to a controllable power source with hybrid CAES systems at affordable electricity costs. Grid-connected wind power can be competitive with the coal-fired power plants through mass local production with fit-size of storage systems with reduced cost of production and improved average capacity factor of wind farm. Using hybrid (wind/diesel, wind/PV) system can supply more reliable and higher quality electricity to rural households compared to wind-only systems in remote area. From international perspective, Greenblatt et al. [41] investigate the feasibility of baseload wind energy by modelling wind farms supplemented by natural gas(single and combined cycle) or CAES systems, they find that ability to compete in economic dispatch can greatly boost the market penetration of wind energy to provide baseload power via wind + CAES.

However, the systems proposed in [16,17]and [41] need to use natural gas in the combustion process of recovered compressed air, one of promising ways to eliminate the combustible-related GHG emissions is to couple wind to CAES and biomass-based storage (gasification to replace fossil combustible) system to improve the performance of carbon-free wind energy with storage system [29], which is extremely relevant for the China's vast rural area where abundant biomass resources exist but are being treated in very inefficient way or wasted. In addition, massive utilisation of natural gas in power generation raises the question about security of supply as most Chinese provinces suffers natural gas supply shortage, as well as geopolitical implications. The other perspective may be backing wind-only power systems with solar energy that is also abundant in west and north China. A review paper in this journal explored the feasibility and economics of wind–solar hybrid system, particularly adapted to road lighting, distributed energy and agricultural irrigation in China [54]. The small scale hybrid system is of particular interest in the Inner Mongolia region where wind power is relatively small in summer and 3–4 times higher in winter, whereas solar power peaks in summer [48]. Thus wind/other renewable hybrid systems can harness the complementary wind and solar/biomass energy resources to produce carbon free electricity to offset partially the incontinence of intermittence due to weather variation (climate uncertainty) from which both solar and wind may suffer.

6.3. Harnessing offshore wind potentials

Globally, offshore wind energy (OWE) offers huge potentials for power generation. Lu et al. estimate that worldwide offshore power potential at 150 PWh per year (in which 4600 TWh for

China), or nearly 8 times global electricity consumption in 2005. Offshore wind farms have advantage of more consistent and less turbulent wind speed [104], which is a key factor influencing the turbines performance and voltage stability. Offshore wind power was considered an important means to ensure the objective of a renewable energy portfolio in the European Union [112].

At the end of 2008, global installed offshore wind power is around 1500 MW [122], with majority in Europe (1441 MW) [115] representing only 1% of global wind capacity. Even in the most developed region-Europe, offshore wind farms still account for only 2% of Europe's total wind capacity [104]. It is expected that 40 GW offshore wind farms could be in operation by 2020 in Europe and could meet 4% of EU's current power consumption [116]. Germany has set an ambitous target to reach 20–25 GW offshore wind power by 2030 [46], Denmark is expected to install 3500 MW offshore by 2010 [104].

As mentioned in Section 2.2, China possesses abundant OWE resources which still remain virtually untapped. The development of large scale onshore wind farms is limited by available land in the densely populated region, whereas offshore farms do not have this constraint. China has already launched OWE development scheme in the East China Sea. The country's first offshore wind farm (34 MW $\times$3 MW), located in Shanghai's near shore, is projected to start operating by 2010. The Shanghai offshore wind farm is expected to produce 267,629 MWh per year, leading to 246,058 tonnes CO_2 emission reduction per year [80,117].

However, costs of offshore wind farms are much higher than onshore(around 50–70% up),both for installation and maintenance costs [104,105], which limit developing the large-scale offshore wind projects. The capital cost of offshore wind turbines ranges between 1800 €/kW and 2500 €/kW, compared to approximately 1200 €/kW for typical onshore turbines [115]. The East China Sea Bridge wind farm's construction cost per kW is more than 3200 US$, much higher than the average onshore wind farm cost in China (approx.1000–1200 US$/kW). Turbine foundation, operation and maintenance costs of offshore wind farms are significantly higher than onshore project due to geographic and transport difficulty. Foundation cost of offshore account for more than 20% of total costs, compared to only 4–6% in onshore wind farms. O&M may represent 30% of overall costs in offshore wind farms [105]. From the long-term perspective, cost of offshore wind energy is expected to decrease along with the technological advancement in turbines design and layout and installation optimization. Junginger et al. [45] used the learning curve method and projected that the investment cost of offshore could decline 25–39% by 2020.

Moreover, offshore wind farms need to address the complex loading due to dynamic changes in wind speed and direction as well as wave speed/height and direction [60]; and the reactive power produced by submarine cable connecting offshore wind farms to onshore power grid [104]. In addition, the frequent strong typhoon occurrence on the eastern shore of China challenges the turbines resistance to inclement tempest strikes. The deeper analysis of value chain of OWE development should be undertaken to formulate policies for the deployment of large offshore wind farms. Development of offshore wind technology requires comprehensive capacity in both academic and industrial knowledge in key turbine components[18] design, wind farm layout, electric power collection, condition monitoring, installation procedures and maintenance strategies, grid integration as well as economics of offshore wind [122].

Experiences cumulated in wind farm development will facilitate knowledge and technology acquisition and costs reduction thanks to the learning by doing procedure. The built offshore wind farms can be used to validate and develop models to improve wind turbines design, site selection and cost–benefit analysis as well as environmental impact assessment[19], *in fine* the contextualised learning-by-doing process can provide significant contribution to the fundamental knowledge of offshore wind technology [122].Further, key characteristics need to be better understood with regard to the techniques of offshore wind farm system design, including the optimization configuration and assessment of rational distribution, electric transmission technology, system insert with operating, wind farm MES, wind turbine bases, etc. [119]. In addition, continued national policy support is determining in OWE development, for example, the large-scale commercial development of offshore wind farm in Europe was implemented after several decades of theoretical studies and experimental development [42]. The long-term R&D programme like the 'Concerted Action on Offshore Wind Energy in Europe' (CAOWEE) is needed in China to foster the popularity of the large scale offshore wind farms. The national strategic wind energy plan incorporating 7.5 GW offshore wind power by 2020 [26], is expected to greatly enhance the OWE development and relevant supply chain formation and job creation. The recently announced Nantong (Jiangsu province) offshore wind turbine equipment production base could become the prototype to catalyse scaled development of OWE technology.

6.4. Wind power pricing and financing

6.4.1. Long-term guarantee of wind electricity pricing

In China, there exist already legal and regulatory frameworks to support renewable electricity connection to power grid, for example, the REL stipulates that power grid company should give priority to purchase the renewable electricity when available at negotiated price. However, the current model of price bidding system in the wind farm concession projects is likely to drive away the most experienced wind energy developers since the price competition will generally result in Nash equilibrium by which the developers can hardly earn profits from wind power projects. Concession project developers are likely to choose the low-cost domestically made turbines and components as well as less efficient management which will undermine the wind farm operating performance. Valuable foreign experiences, in particular in the European countries, may be learnt to improve the current wind power pricing system in China.

As the leading wind power development country, Germany has relatively long experiences in feed-in tariff implementation. The German feed-in law for wind electricity was enacted in 1991 and the Renewable Energy Sources Act (Erneuerbare-Energien-Gesetz/EEG) entered into force in 2000 with recent amendment setting mandatory renewable targets (30% of renewable electricity by 2020) [35]. The EEG is endowed with the provisions that give priority of power grid connection to the electricity generated from renewable resources , including hydropower, wind, solar, and biomass, geothermal as well as landfill, pit and sewage gas. Power incorporation refers to the grid access in either distribution and transmission grid, and power dispatch [38]. Grid operators are obliged to feed in electricity produced from renewable energy and buy it at a minimum price within their supply area. The regulation also introduced a German-wide scheme to equalise these costs incurred by grid operators, as the amount of energy from renewables being fed into the system differs in the various regions. A comparative analysis of the UK's Renewable Obligation and German EEG's feed-tariff shows that

[18] Airfoils, blade, rotor, hub, shaft, main frame, gearbox, generator, control, yaw system, tower, foundation, etc.

[19] Offshore wind farms can have negative impacts on marine mammals and birds, fishes, cold-sensitive or thermophilic benthic species due to artificial magnetic and/or electrical fields occurring at cable connections [46].

feed-in mechanism is more effective in increasing the share of renewable electricity because it can reduce the generator and financier's risk more effectively [109].

By contrast, the long-term feed-in tariff structure has not yet been established in China, although short-term negotiated on-grid tariff has been practiced in some wind power projects. Moreover, the concession processes in wind farm construction need to be improved to render the selection procedure more transparent. selection and electricity price bidding process make foreign players unlikely to engage in large wind farm project financing due to the opaque policy in favour of domestic and in particular the state-owned companies [11,28,71].

6.4.2. Mobilising private and institutional financing

To attract private financing into wind industry, a transparent bidding process and independent third-person monitoring mechanism should be established. As mentioned in Liu et al. [56],specific investment policy scheme such as power purchase agreement (PPA) is necessary to attract private investment in addition to introduction of competition mechanism in the renewable power generation market. With clear terms and conditions of the PPA, the responsibility and advantages for both wind farm developers and financiers and power grid company will be clarified by which the stakeholders can estimate properly the benefits and risks associated with the project development.

In addition, during the period of implementation of "two-plus" policy scheme in the late 1990s, Chinese government disbursed subsidy for wind developers to cover the commercial bank loan interests after completion for the first 1–2 years from the date of operation of wind farms. However, most commercial bank or other financial institutions have so far shown lukewarm interests in wind power development due to high uncertainty about return on capital and unavailable expertise in renewable energy financing, consequently the cost of renewable financing portfolio is still very high. Financial incentives need to be tailored to encourage private financing and commercial banking corporations to invest in wind energy development.

6.4.3. Mainstreaming carbon finance by sectoral crediting

The carbon finance is one of prospective means to attract both domestic and overseas private financiers. The post-Kyoto international climate regime is very likely to be based on sectoral approach (crediting for extra efforts made by developing countries) instead of reaching a global consensus on economy-wide emission caps, the sectoral approaches such as sectoral no-lose target (SNLT) and SD-PAM have been extensively discussed in the existing literature (e.g. Bosi and Ellis [12]; Baron and Ellis [9]; Schmidt et al., [81]; Streck et al., [92]). Power sector is one of key sectors to be targeted in sectoral crediting approach to exploiting untapped mitigation potentials in developing countries. A specific point in the power sector is that the action taken will not produce any carbon leakage issues since electricity is not globally traded goods, such as steel, cement and aluminium.

Fossil fuels-fired power generation is the most important emissions sources in the world [3,102]. Thus it is foreseeable that power will play an overarching role in sectoral approach implementation in post-2012 period. The major sectoral crediting method employed in the power sector will be developed based on the sectoral crediting mechanism and or programmatic CDM model. China is endowed with large potentials for wind CDM implementation. In 2006, more than two-thirds of wind farms installed in China have applied for CDM [32]. In 2008, 90% of wind energy projects have applied for CDM registration, nearly half of wind energy CDM projects in the world are located in China representing two-third of installed capacity in CDM project [97]. As of 1 March 2009, a total of 661 wind energy projects were in the 'CDM pipeline', totalling an installed capacity of 25,8 GW, in which 319 projects are in China , making up almost 17.2 GW of capacity [123]. Nevertheless, some institutional barriers hinder the international players from entering the wind CDM market as the current regulation prevents companies with less than 51% Chinese ownership from taking advantage of CDM to offset their carbon emissions [71].

A reformed CDM scheme needs to be designed in favour of sectoral crediting framework in the power sector to facilitate the issuance of emission credits by bundling a number of similar wind power projects developed in China to simplify the bureaucratic process, facilitate the administration and management (implementation and monitoring) and reduce transaction costs which constitute major hurdle in many CDM projects [32]. A sectoral "no regret" target should be defined in the crediting baseline of developing countries based on national effort with technical and financial assistance from developed countries, it is a *no lose* commitment in the sense that the host country would not bear any penalty if the target is not attained. If the actual emissions level in a sector (e.g. power sector) is below the negotiated target, then tradable emission credits will be generated [38,92], this can be illustrated by graphical representation in Fig. 7.

Under this medium- to long-term sectoral crediting mechanism, carbon finance can play a catalyzing role to decarbonising gradually China's power sector by scaling up wind power investment to accompany power sector's transition to lower emissive electricity generation trajectory.

6.5. Institutional coordination and synergy formation

The effective implementation of wind energy development requires synergy amongst different government institutions and administrations in charge of energy policy coordination , technology, finance, custom tariff, land use (spatial planning) , agriculture, labour as well as academia and industry R&D. A comprehensive policy scheme is to be devised to mobilise all the stakeholders along the whole value chain of wind industry, otherwise the incoherent and uncoordinated actions will hamper the fast development and localisation of wind farms. Significant efforts should be emphasized on domestic capacity building in terms of technological innovation for large-sized turbine manufacturing. Innovation will drive "orphan" research areas such as offshore wind farm and trigger radical market transformation to rapidly adapt novel wind technologies to the climate resilience policy framework [31]. Incentives for innovation and strong political support will be needed to speed up the wind energy development.

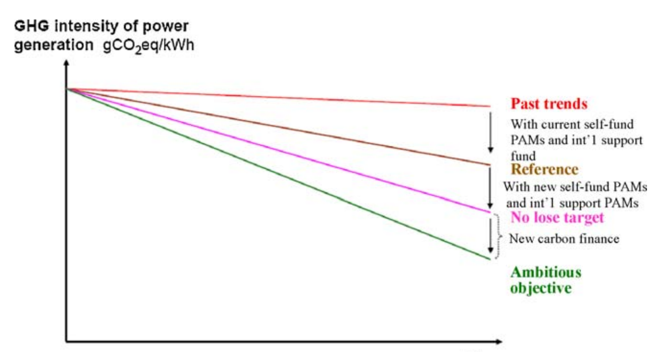

Fig. 7. illustration of sectoral crediting mechanism for carbon efficiency (source: [92]).

6.6. The way forward: strategic growth

A range of technical and institutional barriers mentioned above will need to be cleared in the coming years to scale up wind power deployment. From technical viewpoint, Tavner [59] presents the specific challenge for accelerating wind energy development in the UK's context, however, many of which are also very relevant for developing countries like China. The major challenges include mathematical modelling of complete turbine system; control modelling of turbine; generator and conversion systems; integrated modelling of wind farm and grid system, economic modelling of wind power system to assess the influence of market; weather; technical and operational conditions; reliability modelling of wind power infrastructure; understanding of international market performance of wind resources; implications for penetration of large turbine in power grid and impact of fuel cells nuclear fission or fusion on the survivability of wind power and acquisition of technical know-how and work force capacity building in large wind turbines manufacturing and installation.

Indeed, foreign aid and investment had a stimulatory effect on previous wind energy development in China in the 1980s and 1990s, generating many benefits in terms of technology transfer and international trade and contribution to sustainable economic growth [110]. However, domestic manufacturing of large capacity and performing wind turbines need to be strengthened further to yield lower costs in order to deploy this technology at scale, note that the largest turbines currently operating in Germany have a rated capacity of 6 MW by 2008 [38]. The progress in turbine material, in particular the application of nanotechnology for wind turbine components will allow development of larger wind turbines and improvement in generation efficiency[20]. Moreover, Chinese wind research and industry will need to advance the knowledge development and acquisition of state-of-art technology in variable speed turbines and offshore wind farms. China should develop its own technology patents by creating synergy between academia and industry. Their collaboration will allow triggering innovation and promotion in the whole supply chain. Note that the application of current models for onshore wind turbines may be inappropriate for offshore, which could performer much better provided significant changes in technology [122].

Undoubtedly, there is still a long way forward before the wind energy can make substantial contribution to decarbonising energy supply and reducing the dependency on imported oil and minimising the impact of coal use in power generation in China. The roadmap of future development of wind energy industrialisation can be decomposed into three successive steps as proposed in [95] with indicative timeline in line with the national 5-year plan.

The first phase stretches from 2005 to 2010, China needs to improve the policy framework of wind energy development and complete comprehensive survey of country's onshore wind resources and start the survey of offshore wind resources; as noted in Billinton and Bai [10], the contribution of a WECS to the reliability performance of a generation system is highly dependent on the wind site conditions. The technique of modelling reliability of wind's contribution to power system need to be developed to understand a wide range of determining factors including the wind regime at the site locations, wind speed, the degree of correlation between multiple wind sites and the wind penetration level in power system [125]. More specifically, the simulation of El-Fouly et al. [34]show that wind farm control strategy, penetration level and installation location significantly impact the real-time electricity market prices and the generation revenue as a function of the demand. Thus, the decision on selection of wind farms location has extremely important implications for economic viability of wind power generation.

Chinese wind industrials needs to accelerate the acquisition of advanced techniques of wind farms design configuration and characteristics modelling, key turbine components manufacturing, in particular the technological know-how of the megawatt-scale wind turbine design and manufacturing, strengthen the reliability performance studies of wind and power grid integration,[21] as well as issues relating to grid-connected wind reliability and steady-state behaviour. The characteristics of likely voltage variations challenges the wind turbine manufacturers since in actual operation environment, it is very rare that grid condition remains close to nominal values. The techniques of modelling the voltage and frequency variation on the fixed-speed or variable speed wind turbines power output is of extreme importance. National centres of excellence of wind turbines R&D are to be established rather than simply installing turbine assembling bases in order to promote the domestic wind energy innovation capacity. Cooperation between academia and wind industry must be strengthened.

The technical barriers in offshore turbines development and management need to be removed due to higher cost of foundation infrastructure and maintenance compared with onshore wind farms.

Regarding the large-scale wind farm installation, state-owned or other domestic wind turbine manufacturers should be encouraged to collaborate with wind farm developers in the form of a joint venture, to facilitate the localisation of wind turbines and components manufacturing.

The wind energy development strategy in the second phase (2011–2015) will focus on the offshore wind resources exploitation, which will necessitate carrying out a comprehensive resources survey and technological breakthrough. China should establish the national wind turbine R&D centres to undertake independently the cutting-edge onshore and offshore wind energy technology, including hybrid energy storage and long distance transmission system. Human capital is more important than financial capacity formation since the economic growth theory suggests the accumulation of specialised human capital through learning-by -doing will ensure steadier industrial growth and generate more socioeconomic benefits than simply accumulating the financial capital in economic sector, modelled by a conceptual and theoretical framework that is demonstrated in [61]. Technology know-how dissemination needs to be encouraged by specialised technological learning along the entire supply chain, the overlapped imports of the same foreign product and technology should be avoided to optimise the utilisation of human capital specialisation and allocation of scarce economic resources.

Efficient specialisation in supply chain and human capital accumulation backed by appropriate policies will allow the Chinese wind industry to grow robustly and to compete with international leading wind turbine manufacturers in both domestic and international markets. Note that some Chinese turbine makers have already planned to commercialise their products in the UK and US markets in the coming years. The acquisition of domestic manufacturing capacity of 5 MW scale wind turbines will be a litmus test for Chinese wind industry in the next decade.

In the strategic development plan for the third phase (from 2016 to 2020), building on the efforts in technological learning and scale effect in domestic market exploitation, Chinese turbine industry will be expected to undertake independently wind

[20] Nano-materials can allow improving the physico-chemical properties of wind turbines components such as blade and rotor diameters and improve the efficiency under unfavourable climate condition and extreme weather condition such as low-speed wind, particularly important for wind farms projects in China.

[21] Reliability performance of wind energy depends on various factors : wind regime, sites, wind penetration level, turbine cut-in,rated and cut-out wind speed etc [125].

technology R&D with their own IPRs to enable the long run growth, the built capacity will allow Chinese manufacturers to step into the world wind power market along with international competitors.

7. Conclusion and perspective

In this paper we explored the potential of scaling up wind energy in China and the economic and environmental co-benefits. Key determinants of promoting wind power to decarbonise the power sector in China have been identified. Technical, financial and institutional barriers to wind energy deployment must be addressed with appropriate policies. It is argued that various policy and economic instruments need to be implemented to help foster wind energy development in China in the coming years as most of wind resources potentials remain untapped yet.

Scaled and robust development of wind power will play an increasingly crucial role in enabling sustainable energy supply, contributing to new economic growth and creating green job opportunities as well as cutting GHG emissions in China's power sector. Development of mega wind-power bases and localisation of large turbine manufacturing will facilitate the exploitation of economies of scale in the wind industry to drive down the cost for the purpose of widespread diffusion of this promising carbon-thrifty technology. Importantly, the under-performance of domestically made turbines and grid infrastructure inadequacy may seriously hinder the large-scale development of wind power in China in the foreseeable future. Sound policies and support instruments are required to meet the targets of 100–120 GW or more ambitious goal by 2020.

As argued in [99], electricity supply shortage will constrain seriously the regular pace of economic growth in China, security of energy supply is thus crucial to maintain the socioeconomic development and alleviate poverty in remote areas and environmental pollution mitigation in China, to which wind power can make a substantial contribution, in particular through prioritising the development of large scale wind farms to create economies of scale. The widespread outage of electric power in over 24 provinces in the summer of 2004 revealed the fragility of the conventional electricity supply model that is based on centralised coal-fired power plants and large transmission and distribution networks. Wind is a one of promising way to diversify the electricity supply to minimise the power supply disruption risk and mitigate fossil fuels combustion-related carbon emissions.

Capacity of domestic mass production of large wind turbines and institutional change are required to spread the baseload wind power, it is of particular importance to promote large bases of mass production of wind power (MW turbines and GW-scale wind farms) development combined with large-scale electricity storage and long-distance transmission to deliver 'baseload wind power' in distant electricity demand centres. Locally mass-produced wind power would be cost-competitive with coal-fired power provided that technical and financial barriers can be removed. Scaling up large wind energy development (both grid-connected and stand-alone projects depending upon weather, geographic and economic situation) by implementing comprehensive wind development strategy backed by consistent public policies will generate positive spillover in terms of both environmental and economic benefits.

It is demonstrated that the acquisition of technological know-how in large turbine manufacturing, installation and maintenance, training of labour force and promotion of wind technology R&D as well as modernisation of power grid are the prerequisite of successful penetration of wind energy. Capacity building in the wind industry is of crucial importance, the scaling up of wind power can not be realised without domestic manufacturing of large reliable turbines and electric control systems. Additionally, hybrid models should be developed in the places where wind density evolves as a function of time and can be supplemented by other local fuels. An integrated approach which combines wind and other energy sources such as solar, hydrobiomass and fossil (e.g. diesel; natural gas) backup by efficient storage systems can make wind farm competitive with the conventional coal-fired power plants. The strategic development of offshore wind technology will allow the coastal provinces in the east to diversify the power supply and enhance energy security, as well as reducing the costs related to the construction of long-distance transmission lines connecting mega wind farms in the west to the load centres in the east. A heuristic approach can be applied to encourage the technological innovation and experiences cumulation to keep the installation costs down. Economic efficiency must be attained to scale up both onshore and offshore wind farms development in China.

Different financing tools to support large-scale wind farm development and grid-connected wind electricity are already available, private investment and carbon finance need to be mainstreamed into wind power development projects. The sectoral crediting mechanism is arguably implementable for scaling up the wind penetration in the power generation mix in China in line with the post-Kyoto international climate regime. A well-designed climate financing scheme would deliver technology transfer in Chinese wind industry through rewarding extra effort in wind farm power generation performance and measurable carbon emissions reduction. Wind could be the backbone contributor to the long-term GHG mitigation in China.

Lastly, long-term policy support will be required to accelerate the wind energy development in the context of volatility of fossil prices and growing concerns on global warming caused by large fossil fuel combustion. The success of harnessing wind energy in China will rely on both technological progress and institutional capacity building and innovation. The consistency and relevance of different policy and economic instruments are of crucial importance in facilitating the scale-up of investment in China's wind energy sector in light of curbing GHG emissions in China's power sector. In this respect, a coherent policy framework will significantly contribute to moving China's power sector forward to embark on a sustainable, climate-friendly and innovation-led development trajectory in a carbon-constrained world.

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